AN INSTRUMENT FOR MEASURING RHEOLOGICAL PROPERTIES BY BENDING.

APPLICATION TO FOOD MATERIALS OF PLANT ORIGIN*

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Abstract. A new instrument, the MITEX MK II Bending Tester, is described as a means of measuring the following rheological properties of solid foods: *bending moment, curvature, bending rigidity, modulus of elasticity, curvature set* and *bending moment loss*. Equations applicable to bending and results of measurements on samples of celery, carrot, apple and potato are presented. Changes of the modulus of elasticity in relation to the time of exposure of sample strips to the ambient atmosphere, and graphical and mathematical treatment of the data for estimating a total 'adjusted time' (age) of a particular sample are discussed.

1. Introduction

The study of bending belongs to the engineering discipline of strength of materials as applied to beams (Timoshenko and MacCullough, 1940). In practice, methods employing bending have been reported for the testing of – among other materials – metals (Gohn and Arnold, 1946; Lubahn, 1959; Nunes, 1965), and textiles (Jilla and Backer, 1968; Popper and Backer, 1968). With biological materials, the method has been limited mainly to such applications as the measurement of the critical radius of curvature of tobacco leaf midribs (Suggs *et al.*, 1962) and the measurement of the ultimate bending strength of common pasture plants (McClelland and Spielrein, 1958; Prince *et al.*, 1965). This work is of interest in the design of machines for harvesting and processing (Mohsenin, 1970). In a different application, Somers (1965) used bending with slices of potato tubers, employing the samples as cantilever beams deflecting under their own weight. The objective was to study the effect of different buffer solutions, sucrose and other compounds on the rigidity and strength of the tissue. For this purpose, he employed the reciprocal of the product of the modulus of elasticity and moment of inertia which he defined as the "moment of flaccidity". Occasionally, in different laboratories, use may be made of empirical devices which subject samples (plant tissues, cheese, dehydrated pieces of fruit, potato strips, etc.)

to (a) bending under static load between two spaced supports, or (b) bending under the samples' own weight in a cantilever fashion. In these cases, the measurement of force or deformation is used as an indication of 'crumbliness', 'brittleness', 'breaking strength', or other characteristics (e.g. Heyn, 1940; Bonner, 1960; Tagawa and Bonner, 1957). The 'Droopmeter' developed by Gallop (1971) for measuring the 'droop' or sag of potato french fries operates on a cantilever principle. In a somewhat different approach, Massey et al. (1961) subjected circular discs of lettuce to bending by placing them between the ends of two vertically mounted steel rods and lowering a 'weight' ring around the upper rod in order to make contact and bend the protruding disc. The amount of deflection produced by the weight was used as a measure of crispness, after normalizing for variations in thickness. Bourne et al. (1966) used the Instron Universal Testing apparatus in experiments on potato chips, which were mounted over a 3 cm diam ring and pierced (bent and fractured) by a $\frac{5}{16}$ in. diameter pin. The very steep slope of the initial portion of the force versus deformation curve indicated the high resistance of the crisp chip to bending.

In much of the work on bending, the deflection of the sample necessitates a change in the gage length which causes tensile stresses in addition to those involved in pure bending; also, at least for large deflections, the sample does not form an arc of a circle. As a result, theoretical treatment of the data from the standpoint of pure bending is difficult, if not impossible. Another problem is that most instruments were specifically designed for the particular experiment(s) and are not available for research by other workers.

This paper describes a new instrument for the testing of rheological properties of solid materials by bending and gives a brief account of the theory involved. The instrument is designed to maintain a constant gage length, while subjecting the sample to bending at a constant rate of curvature along the arc of a circle. Measurements are convenient to make and the different rheological properties are easily calculated from the obtained data. Application of the instrument to selected materials of plant origin is also discussed.

2. Instrument and Properties Measured

The instrument used for this purpose is the MITEX MK II Bending Tester*, shown in Figure 1. An early prototype of a similar instrument was applied to the measurement of the rheological properties of textiles (Jilla and Backer, 1968). The testing of the sample is performed on the right side of the front panel, while the left part serves as the control section. The sample is mounted between two edges of the movable holder seen at the left end of the cam slot; the fixed supports and the bending moment transducer cantilever are located behind and beside the white Teflon plug. The black dial above the test section sets the curvature rate, and the meter fixes the upper and the lower curvature limits. Switches program the test. Inside the enclosure

* Manufactured by IDR Enterprises, Inc., 1211 Highland Ave., Needham, Mass. 02192, U.S.A.

is a control circuit, a regulated power supply, a precision gear train moment transducer microcircuit, and a curvature transducer. Power and output cables connect in the rear of the unit.

The arrangement for the mounting of the sample is an important part of the apparatus. It consists of two pairs of wedge-like supports, one pair stationary and the other movable. The sample, in the form of a rectangular strip, is positioned
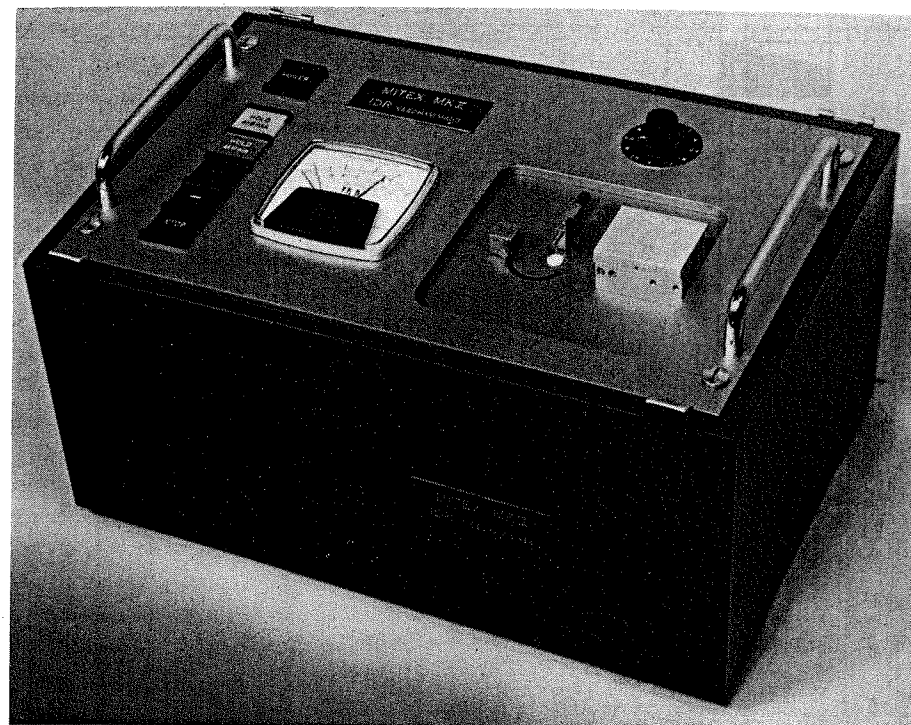

Fig. 1.   Photograph of the MITEX MK II Bending Tester.

between the two pairs of supports as shown in Figure 2. The stationary supports are on the right and the movable ones on the left. As the latter move along a cam slot, the deforming sample describes an arc of a circle whose curvature is changing at a constant rate. A capacitor-type transducer connected to one of the stationary supports is used for measuring the bending moment, while a precision potentiometer is used for measuring the curvature. An X-Y recorder plots the two variables. Bending is followed by bending recovery, as a result of which a hysteresis loop may be recorded.

Figure 3 shows a sample bent to six curvature levels. Distance G is the gage length. One pair of sample supports – small triangles – executes a rotation and a translation, while the other pair is stationary.
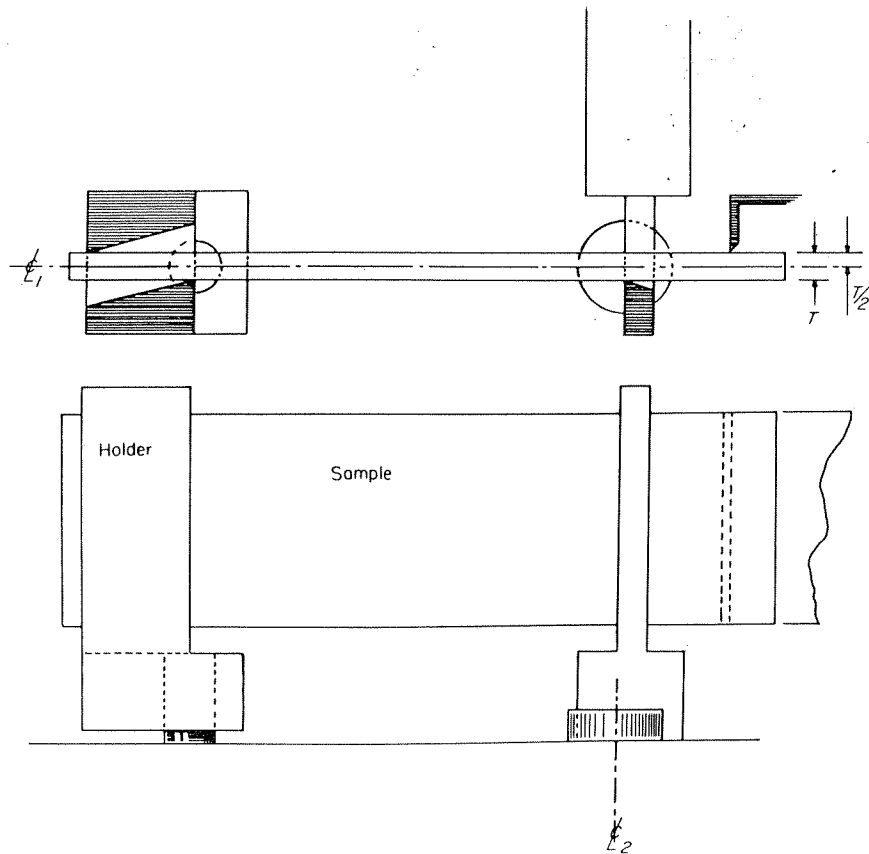
Fig. 2.   Diagram of sample mounting assembly. Bottom: side view. Top: top view. T = thickness of the sample.

Fig. 3.   Schematic representation of sample bent at six curvature levels. G = gage length, K = curvature expressed as in^{-1}.
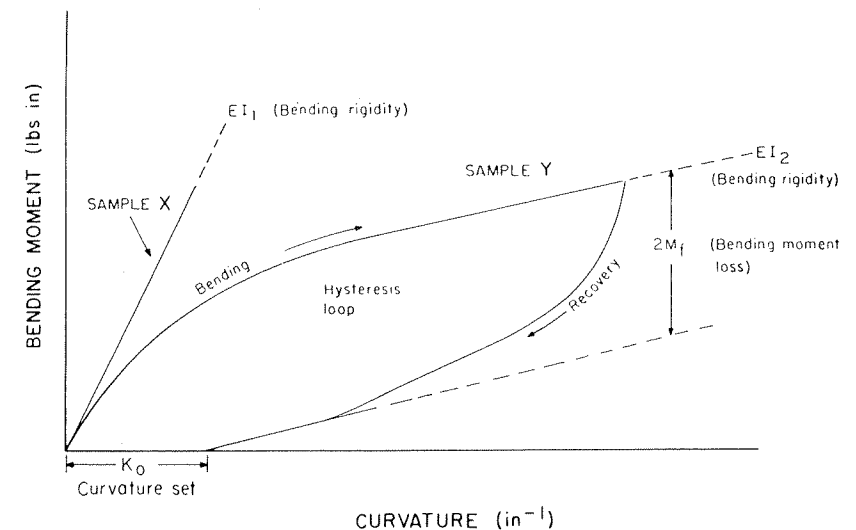
Fig. 4.   Typical loading-unloading curves obtained with the instrument.

Figure 4 shows two typical plots obtained with the instrument. The slopes EI_1 and EI_2 represent the 'bending rigidities' of two samples, where E is the modulus of elasticity and I is the moment of inertia. The larger the bending rigidity, the stiffer is the sample. As shown in Figure 4, sample X exhibits linear behavior in contrast to sample Y which exhibits hysteresis. In the latter case, the vertical distance between the two dashed parallel lines is a measure of the bending moment loss $2M_f$, and the distance K_0 is a measure of the curvature set. (In fabrics, the ratio $EI/2M_f$ is occasionally used as an indication of 'feel to touch' – a small ratio being desirable). If Figures 3 and 4 were related to an actual experiment with sample Y, the curvature at the origin in Figure 4 would have a value of $K=0$ and at the end of bending (before the recovery part of the cycle begins) a value of $K=4.18$ in^{-1}. The intermediate points along the curvature axis which correspond to the other K values of Figure 3 would be linearly distributed.

Although this is not the case in Figure 4, materials having a 'yield point' (Mohsenin, 1970) would have shown a point in the bending part of the cycle beyond which an increase in strain would have occurred without any increase in stress. In the absence of a true yield point in Figure 4, the straight line (EI_2) could be extended to obtain the intercept with the ordinate. Also, the slope (first derivative) of the curve could be plotted versus the curvature to detect the possible existence of any maxima or minima. Although not done in this work, this treatment may be useful in practice e.g. when relationships between mechanical measurements and sensory or other data are studied.

Figure 5 shows an interpretive diagram and a number of equations related to bending. The first equation applies to the motion of the sample supports; it shows that the sample forms a circular arc of constant length. The second equation indicates that the curvature is a function of the rotation angle; therefore, a constant angular velocity produces a constant curvature rate. The remaining equations show the

EQUATIONS	
$r = \dfrac{G}{\theta}\sin\theta$	(1)
$K = \dfrac{1}{\rho} = \dfrac{2\theta}{G}$	(2)
$\rho = \dfrac{EI}{P\ell} = \dfrac{EI}{M}$	(3)
$M = EI\,K$	(4)
$\sigma = \dfrac{MT}{2I}$	(5)
$\epsilon = \tfrac{1}{2}KT$	(6)

LEGEND:

r, θ - polar coordinates   I - moment of inertia
G - sample gage length   σ - stress
K - curvature   ∈ - strain
ρ - radius of curvature   T - sample thickness
P - load   M - bending moment
E - modulus of elasticity   EI - bending rigidity
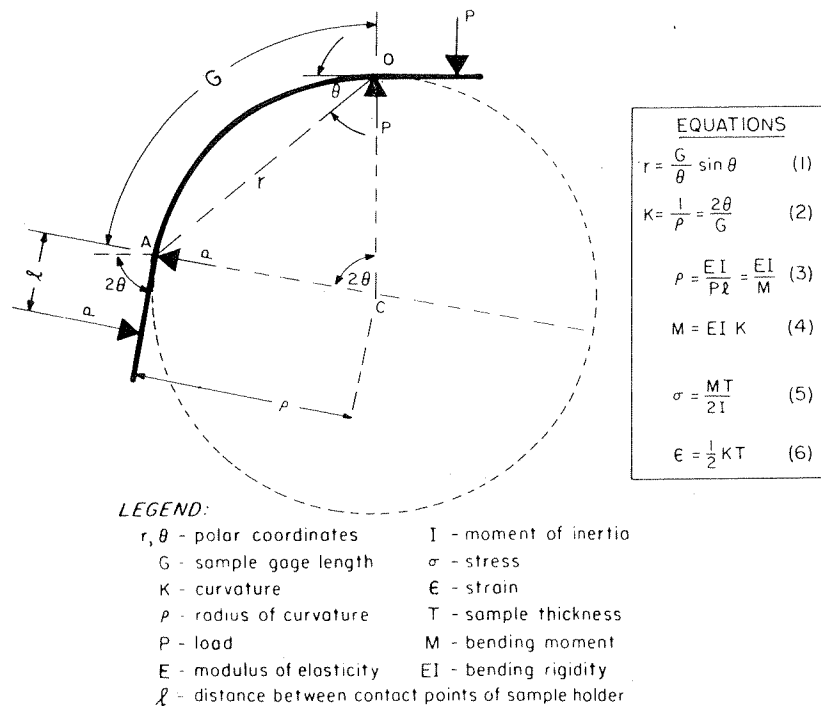ℓ - distance between contact points of sample holder

Fig. 5.   Interpretive diagram and equations related to bending.

relationships between the bending moment and the curvature generally applicable to the bending of a beam (Timoshenko and MacCullough, 1940). Briefly, this is as follows:

Consider a homogeneous beam bent in the manner of Figure 6, where the moduli of elasticity in tension and compression are assumed to be equal. The maximum strain caused by this bending is equal to the change in length per unit length between arcs pq and mn; it is also equal to the change in length per unit length between arcs pq and rs. Since arc pq passes through the center of the section, its length remains unchanged on bending. Thus, the maximum strain becomes:

$$e_{max} = \frac{rs - pq}{pq} = \frac{\left(\varrho + \dfrac{T}{2}\right)\theta - \varrho\theta}{\varrho\theta} = \frac{T}{2\varrho} = \tfrac{1}{2}KT \tag{1}$$

where $K = 1/\varrho$ is the curvature of the bent sample and T is the thickness. On the basis of Hook's law, stress σ is proportional to strain e, or $\sigma = Ee$, where E is the modulus of elasticity. Thus:

$$\sigma_{max} = E\,(1/2KT). \tag{2}$$

Stress at any point in the beam is proportional to its distance y from the neutral axis. (The neutral axis lies in the surface that is perpendicular to the radius of curvature
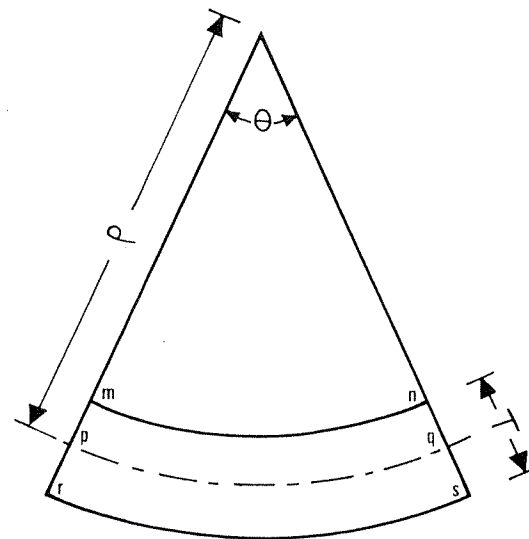
Fig. 6.   Diagram of bent beam. θ = rotation angle, ϱ = radius of curvature, T = thickness of beam.

ϱ and passes through the center pq of the beam.) Substituting y for $\tfrac{1}{2}T$ in Equation (2) gives:

$$\sigma = EKy. \tag{3}$$

For an element of area dA, which is at a distance y from the neutral axis, the force is:

$$dF = (EKy)\,dA. \tag{4}$$

This force distribution produces a resisting couple that balances the external couple dM. Thus,

$$dM = y\,dF = y\,(EKy)\,dA. \tag{5}$$

Summation of these moments over the cross section gives the bending moment:

$$M = \int dM = \int y\,(EKy)\,dA, \quad \text{or} \quad M = EK \int y^2\,dA. \tag{6}$$

The moment of inertia I of a cross-section about its neutral axis is:

$$I = \int y^2 \, dA.$$

Substitution in Equation (6) leads to:

$$M = EKI, \quad \text{or} \tag{7}$$

$$\varrho = \frac{EI}{M}. \tag{8}$$

In the apparatus, the bending moment M is the product of the load P and the distance l (Figure 5). Thus, the radius of curvature can be written as:

$$\varrho = \frac{EI}{Pl}. \tag{9}$$

Solution of Equation (7) for the product EK gives $EK = M/I$. Substitution of this expression in Equation (2) gives:

$$\sigma_{max} = \frac{MT}{2I}. \tag{10}$$

3. Experimental

Fresh samples of celery, carrots, apples, and potatoes were purchased from the local supermarket and placed in the refrigerator until ready for use. To prepare a sample for testing, convenient intermediate sections were cut with a knife; from these sections a final rectangular flat strip was excised and shaped for mounting on the instrument, using a razor blade rigidily mounted at an adjusted distance above a solid support. This distance controlled the thickness of the sample. In most cases, the dimensions of the sample strip were 1.750 in. long × 0.250 in. wide × 0.039 in. thick. The gage length of the instrument (distance between the two pairs of sample supports) was 0.5 in. The rectangular strip of a food sample, mounted between the two pairs of sample supports as shown in Figure 2, was subjected to bending at a curvature rate of 8.37 in^{-1} min^{-1}, up to a maximum curvature of 2.80 in^{-1}. For all samples examined, this maximum was below the rupture point. After reaching the maximum curvature, the sample was unloaded at the same rate yielding a mechanical hysteresis loop. The time for one cycle was 40 s. Several successive loading-unloading cycles were obtained on the same sample. In some cases, a specified waiting time between cycles was allowed. For a test of stress relaxation, the cycle was stopped at the point of maximum curvature, and the relaxation of the sample (decreasing bending moment) was followed with time.

The term 'testing time' refers to the time elapsed from the moment the first bending cycle began. This was the time which could be accurately controlled using a stopwatch. The sample existed during this time in the form of a rectangular strip of specified dimensions and was exposed to the atmosphere of a room cubicle designed for the

control of both temperature and relative humidity. The former was kept at 70 °F and the latter at 40% in all tests. Under these conditions, loss of moisture and changes in the mechanical properties of the sample strip took place. Since the same specimen remained mounted in the instrument throughout the cycles of a particular test, these changes could be accurately followed.

In contrast to the above control of the testing time, the preparation time ranged from 2 to 5 min; this depended on (a) differences in the original shape of the larger 'stock' samples from which an intermediate section and a subsequent rectangular strip were finally excised and formed for mounting, and (b) variations in the speed with which the experimenter could work. Similar difficulties may, of course, be encountered with other instrumental methods. Automation of the sample cutting technique through the use of a proper microtome, which can accurately control the thickness in the range of 1–3 mm for different food materials, may reduce, although not eliminate, this variability. (Microtomes used for histological work and commercial food slicers were found inadequate for this purpose, since they applied to too low or too high a range of thickness.) It should also be taken into account that samples exposed for exactly the same time during the preparation stage may have changed differently depending on their size and geometry (total surface area, presence of grooves, etc.). In this work, an effort was made to ascertain the original (immediately upon cutting) modulus of elasticity of a sample by graphical transposition and extrapolation of the curves, as will be discussed later.

A Moseley model 135M X-Y recorder was used. The coordinates of the curves obtained by this recorder were expressed in terms of 'bending moment' as the ordinate versus 'curvature' as the abscissa, using the calibration factor of 1 mV $= 5.0 \times 10^{-6}$ lb in. for the bending moment and 1 mV $= 4.5 \times 10^{-3}$ in^{-1} for the curvature. These curves were treated as follows: The best straight line was drawn along the upper section of the loading branch of the curve, as in Figure 4. The slope of this line, expressed in lb in^2, is the *bending rigidity EI*, where E is the modulus of elasticity and I is the moment of inertia. The *modulus of elasticity* was calculated from the product EI using the equation $I = \frac{1}{12} bT^3$, where b is the width and T is the thickness of the rectangular strip of sample. A second straight line was drawn along the unloading branch, parallel to the first line. The vertical distance between the two lines, expressed in lb in., is the *bending moment loss*.

4. Results and Discussion

An example of the type of curves obtained with the instrument on a food material is shown in Figure 7. These curves are exact drawings of actual chart curves, with the coordinates expressed in terms of bending moment and bending curvature, as explained above. In this particular sample, the fact that the loading part of the first cycle does not start at the origin is probably due to a slight pressure on the force measuring system, which registers a positive reading on the bending moment axis. This could affect the value of the curvature set which was not measured in this work.
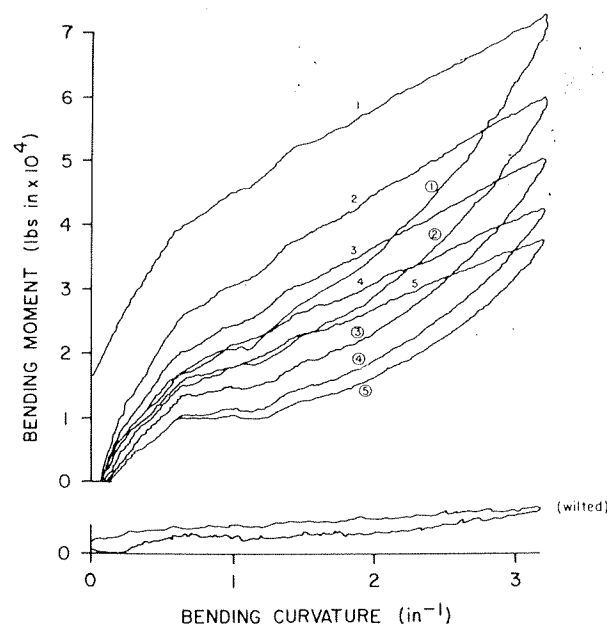
Fig. 7. Instrument curves obtained on a raw potato sample. Circled numbers indicate the unbending part of each cycle. Wilted sample refers to a potato strip wrapped in polyethylene film and kept in refrigerator overnight.

An extreme case of a 'wilted' tissue is included for illustration; this represents a sample which was sliced in the form of a strip, wrapped in polyethylene film and kept in the refrigerator overnight.

Values for the different mechanical properties obtained in relation to the bending cycle and to the testing time (time from the moment the first testing cycle began) are shown in Figure 8 for celery and in Tables I, II, and III for the carrot, apple, and potato, respectively. In general, the values for the modulus of elasticity (E) obtained from the first bending cycle are close to those reported in the literature and obtained by other methods (Finney, 1969; Shipman et al., 1971).

Figure 8 shows plots of the modulus of elasticity *versus* the testing time of celery strips obtained randomly from different stalks without reference to position or other variables. The points of each curve indicate consecutive bending cycles on the same strip. The bottom curve (sample No. 9) refers to a sample which had the longest time of exposure to the room atmosphere before being tested; this sample was exposed in the form of a 2 in. long section of a stalk to the ambient atmosphere of 70 °F and 40% *RH* for about 50 min before a rectangular $1.750 \times 0.250 \times 0.047$ in. strip was excised and mounted on the instrument for testing. All other samples had a 2–5 min preparation time, as explained in the experimental procedure. Comparison of the different curves reveals a trend for the slopes to decrease with decreasing *E*

TABLE I
Values of rheological properties obtained by bending of sample strips from carrot roots

Sample	Bending cycle	Testing time (min)	Bending rigidity $EI \times 10^{6a}$ (lb in²)	Modulus of elasticity E^{b} (lb in²)	Bending moment loss (lb in × 10³)
1	1	0.00	3836.9	3018.8	3.70
	2	0.67	3673.9	2890.6	2.70
	3	1.33	3317.1	2609.8	2.42
	4	2.00	2951.5	2322.2	2.11
	5	2.67	2629.9	2069.2	2.05
2	1	0.00	2180.6	1715.7	2.40
	2	0.67	2229.0	1753.7	2.02
	3	1.33	2105.7	1656.7	1.78
	4	2.00	1977.9	1556.2	1.65
	5	2.67	1859.0	1462.6	1.56
3	1	0.00	3374.4	2654.9	2.55
	2	0.67	3127.7	2460.8	1.80
	3	1.33	2823.7	2221.6	1.64
	4	2.00	2496.9	1964.5	1.48
	5	2.67	2321.5	1826.5	1.30
4	1	0.00	3365.6	2648.0	2.66
	2	0.50	3550.6	2793.5	2.05
	3	1.00	3259.8	2564.8	1.81
	4	1.50	3013.2	2370.7	1.68
	5	2.00	2817.1	2216.4	1.82
5	1	0.00	1678.4	1320.5	1.96
	2	0.67	1955.9	1538.9	1.46
	3	1.33	1861.2	1464.4	1.38
	4	2.00	1801.7	1417.5	1.29
	5	2.67	1709.2	1344.8	1.22
6	1	0.00	5383.2	4235.4	3.84
	2	3.50	3929.4	3091.6	2.68
	3	7.00	2321.5	1826.5	1.80
	4	10.50	1726.8	1358.6	1.36
	5	14.00	1303.9	1025.9	1.05
7	1	0.00	3634.3	2859.4	2.40
	2	3.67	2343.6	1843.9	2.18
	3	7.33	1779.7	1400.2	1.65
	4	11.00	1207.0	949.6	1.40
	5	14.67	797.3	627.3	1.14
8	1	0.00	4832.5	3802.1	3.18
	2	10.67	1237.9	974.0	1.48
	3	21.33	541.8	426.3	0.60

ª Sample dimensions $1.750 \times 0.250 \times 0.039$ in. $I = 1.271 \times 10^{-6}$ in⁴
ᵇ Literature range 2900–5220 lb in⁻² (Finney, 1969).

values. With few exceptions (e.g. sample 12), the curves can be classified approximately into three groups: steep slope (top curves), intermediate slope (middle curves), and low slope (bottom curves). The most important characteristic of each group is that, in general, the process of bending seems to have only a slight or a negligible effect

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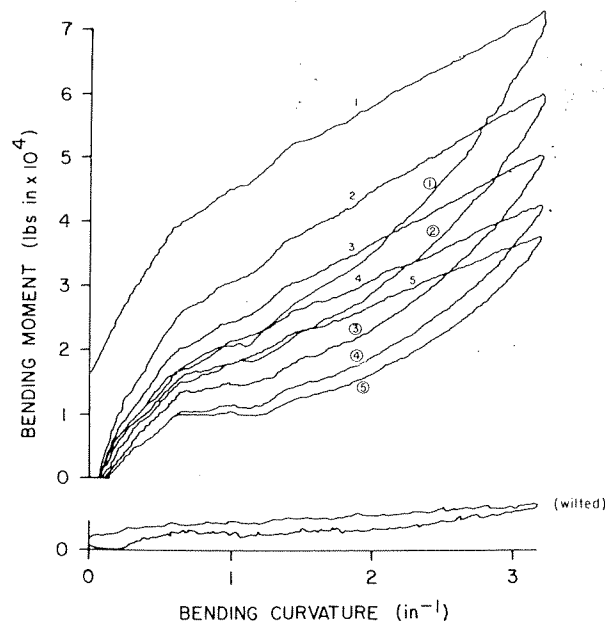
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	5	2.67	2321.5	1826.5	1.30
4	1	0.00	3365.6	2648.0	2.66
	2	0.50	3550.6	2793.5	2.05
	3	1.00	3259.8	2564.8	1.81
	4	1.50	3013.2	2370.7	1.68
	5	2.00	2817.1	2216.4	1.82
5	1	0.00	1678.4	1320.5	1.96
	2	0.67	1955.9	1538.9	1.46
	3	1.33	1861.2	1464.4	1.38
	4	2.00	1801.7	1417.5	1.29
	5	2.67	1709.2	1344.8	1.22
6	1	0.00	5383.2	4235.4	3.84
	2	3.50	3929.4	3091.6	2.68
	3	7.00	2321.5	1826.5	1.80
	4	10.50	1726.8	1358.6	1.36
	5	14.00	1303.9	1025.9	1.05
7	1	0.00	3634.3	2859.4	2.40
	2	3.67	2343.6	1843.9	2.18
	3	7.33	1779.7	1400.2	1.65
	4	11.00	1207.0	949.6	1.40
	5	14.67	797.3	627.3	1.14
8	1	0.00	4832.5	3802.1	3.18
	2	10.67	1237.9	974.0	1.48
	3	21.33	541.8	426.3	0.60

[a] Sample dimensions $1.750 \times 0.250 \times 0.039$ in. $I = 1.271 \times 10^{-6}$ in⁴
[b] Literature range 2900–5220 lb in⁻² (Finney, 1969).

values. With few exceptions (e.g. sample 12), the curves can be classified approximately into three groups: steep slope (top curves), intermediate slope (middle curves), and low slope (bottom curves). The most important characteristic of each group is that, in general, the process of bending seems to have only a slight or a negligible effect

TABLE II

Values of rheological properties obtained by bending of sample strips from a single apple
(McIntosh, late season)

Sample	Bending cycle	Testing time (min)	Bending rigidity $EI \times 10^{6}$ [a] (lb in^2)	Modulus of elasticity E [b] (lb in^{-2})	Bending moment loss (lb in $\times 10^3$)
1	1	0.00	265.63	209.0	0.272
	2	0.67	251.54	197.9	0.208
	3	1.33	222.90	175.4	0.175
	4	2.00	201.76	158.7	0.150
	5	2.67	179.73	141.4	0.128
2	1	0.00	618.93	487.0	0.570
	2	0.67	621.13	388.7	0.465
	3	1.33	570.91	449.2	0.395
	4	2.00	533.91	420.1	0.462
	5	2.67	451.97	355.6	0.284
3	1	0.00	306.16	240.9	0.350
	2	0.67	296.91	233.6	0.268
	3	1.33	273.12	214.9	0.270
	4	2.00	247.57	194.8	0.250
	5	2.67	229.07	180.2	0.226
4	1	0.00	140.09	110.2	0.270
	2	5.67	59.47	46.78	0.154
	3	11.33	23.35	18.37	0.130
	4	17.00	6.17	4.85	0.100
5	1	0.00	359.02	282.5	0.298
	2	5.67	172.24	135.5	0.150
	3	14.33	58.59	46.10	0.085
	4	26.00	25.11	19.76	0.060
	5	37.67	10.57	8.32	0.055
6	1	0.00	376.64	296.3	0.335
	2	5.67	135.68	106.8	0.130
	3	11.33	56.39	44.37	0.038
	4	17.00	29.07	22.87	0.040
	5	22.67	11.01	8.66	0.030
7	1	0.00	466.07	366.7	0.432
	2	3.67	301.76	237.4	0.268
	3	7.33	174.45	137.3	0.195
	4	11.00	97.80	76.95	0.124
	5	14.67	65.20	51.30	0.082

[a] Sample dimensions $1.750 \times 0.250 \times 0.039$ in. $I = 1.271 \times 10^{-6}$ in^4
[b] Literature range 580–1740 lb in^{-2} (Finney, 1969).

on the modulus of elasticity. Compare for example sample 8 with sample 11. After about 3 min, sample 8, which was bent five times, showed a drop in the E value of about 620 lb in^{-2}. Sample 11, which was bent only once, showed an E drop of about 670 lb in^{-2}. Similar changes occur for the other curves except for sample 12, which showed a smaller slope probably due to the natural variability of the material and other unknown reasons. It appears that the factor which has an overriding effect

TABLE III

Values of rheological properties obtained by bending of sample strips from potato tubers

Sample	Bending cycle	Testing time (min)	Bending rigidity $EI \times 10^{6}$ [a] (lb in^2)	Modulus of elasticity E [b] (lb in^{-2})	Bending moment loss (lb in $\times 10^3$)
1	1	0.00	143.17	112.6	0.338
	2	0.67	180.61	142.1	0.280
	3	1.33	184.14	144.9	0.270
	4	2.00	185.90	146.3	0.268
	5	2.67	182.38	143.5	0.265
	6	3.33	168.28	132.4	0.265
	7	4.00	169.60	133.4	0.258
2	1	0.00	148.68	117.0	0.300
	2	0.67	179.29	141.1	0.218
	3	1.33	176.21	138.6	0.210
	4	2.00	174.89	137.6	0.200
	5	2.67	170.48	134.1	0.196
	6	3.33	169.16	133.1	0.184
	7	4.00	164.09	129.1	0.178
3	1	0.00	480.17	377.8	0.885
	2	0.67	591.18	465.1	0.710
	3	1.33	575.76	453.0	0.655
	4	2.00	559.46	440.2	0.620
	5	2.67	528.62	415.9	0.602
	6	3.33	531.27	418.0	0.565
	7	4.00	497.79	391.7	0.552
4	1	0.00	370.48	291.5	0.588
	2	5.67	376.20	296.0	0.428
	3	11.33	301.32	237.1	0.510
	4	17.00	229.95	180.9	0.448
	5	22.67	216.30	170.2	0.467
	6	28.33	174.45	137.3	0.290
5	1	0.00	812.32	639.1	0.828
	2	5.42	567.39	446.4	0.775
	3	11.09	314.53	247.5	0.520
	4	16.76	184.14	144.9	0.336
	5	22.43	118.94	93.6	0.202
	6	28.10	47.58	37.4	0.235
6	1	0.00	742.28	584.0	0.735
	2	5.58	680.16	535.1	0.645
	3	31.17	55.95	44.0	0.480
7	1	0.00	596.90	469.6	0.725
	2	5.67	361.23	284.2	0.492
	3	11.33	292.95	230.5	0.345
	4	17.00	244.05	192.0	0.294
	5	22.67	185.02	145.6	0.172

[a] Sample dimensions $1.750 \times 0.250 \times 0.039$ in. $I = 1.271 \times 10^{-6}$ in^4
[b] Literature range 725–2030 lb in^{-2} (Finney, 1969).

on the characteristics of these curves is the loss of water by the sample strip due to exposure to the ambient atmosphere – fresh samples showing higher E values and steeper slopes. Sample 9, which had the longest exposure, showed the lowest modulus of elasticity and slope. (The reason for a slight initial rise of some curves is not clear at the present time.)
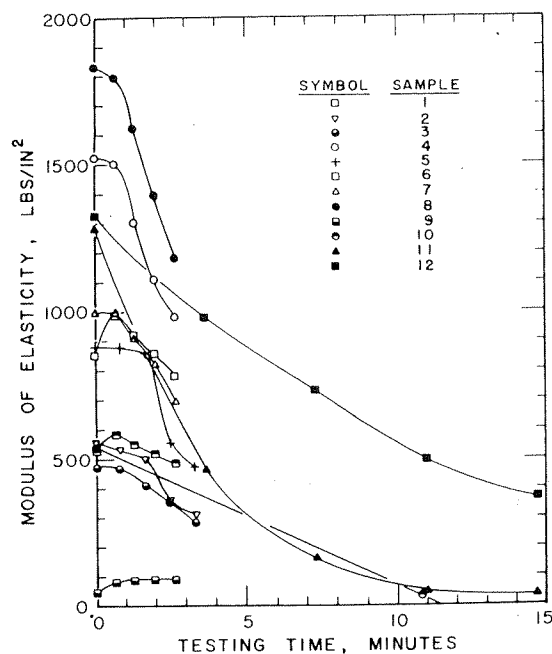

Fig. 8. Effect of exposure to a controlled room atmosphere on the modulus of elasticity of sample strips from celery stalks. (Dimensions: $1.750 \times 0.250 \times 0.039$ in. for sample No. 1; $1.750 \times 0.250 \times \times 0.047$ in. for samples Nos. 2–12.)

If the change in the modulus of elasticity is closely related to the loss of water, this change must reflect the alterations of the 'turgor properties' of the material. This is based on the fact that the amount of water and the pressure exerted by it in the physico-chemical interaction with cellular components determine the distention and resiliency, i.e. the turgor properties of the cell. Similar to the previous work (Kapsalis et al., 1970), the water here has an important bearing on the structural-textural properties of solid foods. These properties can be defined effectively on the basis of mechanical measurements obtained when the food is subjected to different mechanical operations. Bending, in addition to compression, penetration, etc., appears to be a suitable operation for materials of plant origin and possibly for other types of foods.

Because of variations in the time necessary for sample preparation and in the effects of sample geometry on moisture loss during this time, it would be desirable to be able to ascertain the initial modulus of elasticity immediately upon cutting. In

exploring this possibility, it was assumed that the preparation times were randomly distributed. Based on this assumption and on the observation that the different slopes decreased with decreasing E values, the curves of Figure 8 were laterally transposed along the time axis with the purpose of reaching a maximum density of points. Figure 9A shows that a drying-type curve results, due to the loss of moisture and other changes in the material upon exposure to ambient conditions. Although this lateral transposition is empirical and it may comprise differences other than those due to exposure, attainment of this type of fit in a variable biological material is noteworthy.
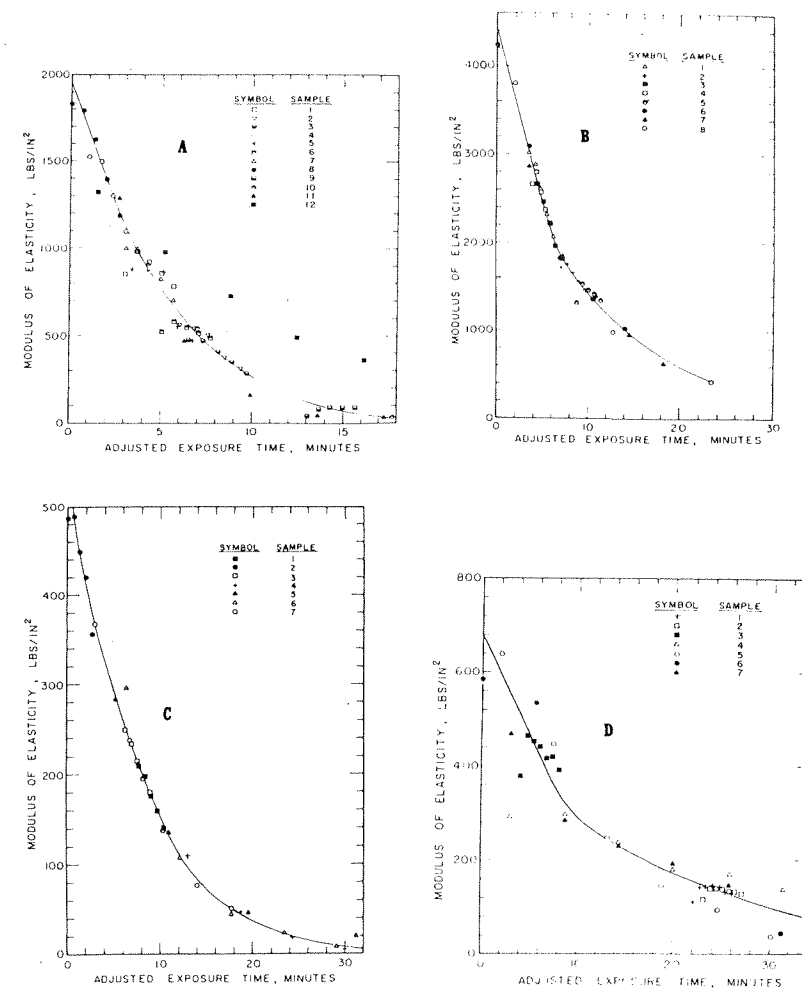

Fig. 9. Plots of adjusted exposure time (including preparation time) versus modulus of elasticity; (A) celery stalks (symbols as in Figure 8); (B) carrot roots; (C) single apple (McIntosh, late season); (D) potato tubers.

Considering sample 9 as an example, the curve in Figure 9A indicates that the changes involved by exposing a 2 in. long section of a celery stalk of a particular geometry and surface area to an ambient atmosphere of 70°F and 40% *RH* for 50 min, plus the changes involved in preparing from this section a sample strip of $1.750 \times 0.250 \times 0.047$ in. and mounting it on the instrument until ready for testing, are equivalent to changes which take place in a strip of sample of the same dimensions exposed to the same ambient conditions for 13 min. Such a curve makes possible the comparison of all samples on the same basis, irrespective of history, size, shape and other variables affecting the intermediate sections. Graphical extrapolation of the curve to zero time indicates that an average value for the initial modulus of elasticity immediately upon cutting is of the order of 1950 lb in^{-2}. To check whether extrapolation to such a high value was reasonable, a limited number of samples from different celery stalks were obtained making a special concentrated effort to keep the preparation time to a minimum. The E value ranged from about 1440 to about 4580 lb in^{-2}, except for one extremely rigid sample which showed a value of 6240 lb in^{-2}.

In previous work (Shipman *et al.*, 1971), the range of *E* values obtained on fresh celery using the Instron Universal Testing apparatus in compression testing was 650–1220 lb in^{-2}. In those experiments, an average preparation time of about 4 min was involved. This shows the need for minimizing the time of sample preparation even when other testing methods are employed.

A similar transposition of the data in Tables I–III resulted in Figures 9B, C, D for carrot, apple and potato tissue, respectively. Extrapolation of the curves to zero time resulted in initial values of the modulus of elasticity of 4400 lb in^{-2} for the carrot (different roots), 540 lb in^{-2} for the apple (single McIntosh apple, late season), and 680 lb in^{-2} for the potato (different tubers).

Mathematical expressions for the above data are shown in Table IV. The polynomial functions were determined by the method of least squares using a computer program, whereas the exponential functions were calculated by the method of successive

TABLE IV

Mathematical functions of modulus of elasticity *E* obtained by bending *versus* adjusted time *t* of exposure of samples to room atmosphere

Food	Function
Celery	
Polynomial	$E = 1837 - 287.3\,t + 16.91\,t^2 - 0.4137\,t^3 + 0.00351\,t^4$
Exponential	$E = 5100\,e^{-0.2877\,t} - 3350\,e^{-0.4109\,t}$
Carrot	
Polynomial	$E = 4414 - 491.0\,t + 20.65\,t^2 - 0.1124\,t^3 - 0.008\,t^4$
Exponential	$E = 3420\,e^{-0.08850\,t} + 1180\,e^{-0.3526\,t}$
Apple	
Polynomial	$E = 505.6 - 51.65\,t + 1.959\,t^2 - 0.03136\,t^3 + 0.00174\,t^4$
Exponential	$E = 1090\,e^{-0.1673\,t} - 585\,e^{-0.2418\,t}$
Potato	
Polynomial	$E = 562.3 - 20.11\,t - 1.151\,t^2 + 0.0872\,t^3 - 0.00146\,t^4$
Exponential	$E = 490\,e^{-0.05469\,t} + 232\,e^{-0.2539\,t}$

residuals (Mohsenin, 1970). Zero time values for the modulus of elasticity of the different foods calculated either from the polynomial or the exponential functions are close to those obtained by the graphical extrapolation. The mathematical expressions are also useful in determining quantitatively the probable age of a particular sample on the basis of an independent measurement of the modulus of elasticity.

It should be emphasized that both the curves and the mathematical functions presented here apply strictly to the changes of sample strips of specified dimensions under the laboratory conditions described. However, similar relationships could be established for actual storage studies of fresh produce; in this case the abscissa scale may be in terms of days, weeks or months. It is expected that the quantitative features of the curves will depend on the variety, season and other conditions. Based on this information, 'average' curves may be constructed which, in combination with other tests, can be of practical value in ascertaining the stage of deterioration ('how old is the sample') and predicting the remaining shelf life of the food.

In earlier work (Shipman *et al.*, 1971), the high correlation obtained between sensory 'crispness' of celery and modulus of elasticity using the Instron in compression testing indicates the fruitfulness of further research in this area. Of particular interest will be the possible relationships between mechanical measurements as obtained by bending and other sensory descriptions such as 'limpness', 'snappiness', and 'crunchiness'. In this application, not only the modulus of elasticity but the bending moment loss (hysteresis), which indicates the amount of energy dissipated by the material as heat upon bending and unbending, may be of importance. There was some indication in the present experiments that the change in the bending moment loss due to the loss of water from the sample was smaller than the change in the modulus of elasticity. However, plotting of the data showed that this trend was not consistent; therefore,
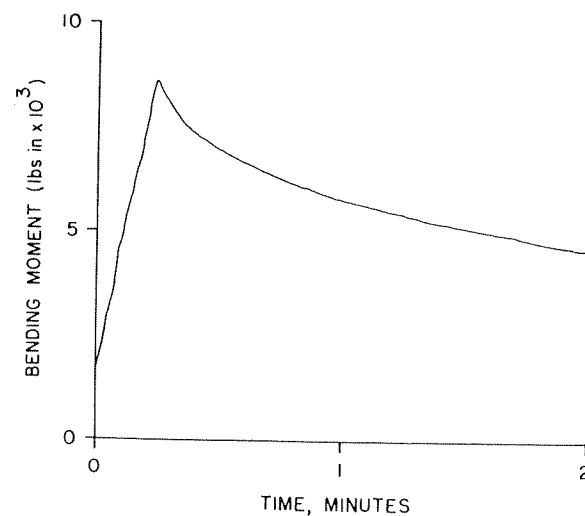

Fig. 10.   Instrument stress relaxation curve obtained on raw carrot.

more work on the significance and applicability of this property is necessary. Other properties which remain to be investigated include the curvature set and the ratio of bending rigidity to the bending moment loss.

The curve for stress relaxation using the method of bending (Figure 10) is of the same general nature as that obtained by other methods (Mohsenin, 1970); it is amenable to a similar mathematical treatment.

5. Advantages and Limitations

An advantage of the instrument is that measurements of rheological properties can be obtained on the same (or replicate) sample, and the effects of different variables such as moisture, relative humidity, temperature and different chemicals can be followed with time. A separate temperature control chamber for the range −100 to 400 °F is available, and chambers for the control of headspace environments (relative humidity, different gases) can probably be constructed. The mounting of the sample is simple; all that is needed is a good alignment. The instrument can be programmed to run tests in single or several cycles, or to perform tests of bending relaxation. When the sample thickness is constant, about twenty single cycle tests can be carried out in one hour. Tests may be stopped manually at any point, and they can be reversed automatically at different levels of curvature. The original data in the form of the X-Y recorder plots can become the final test records by writing down the scale factors for each axis.

Difficulties were encountered with heterogeneous specimens due to non-uniform bending and to buckling during loading and unloading. When a sample is curled or wrinkled, the geometry of Figure 5 is not satisfied and, therefore, the plots of bending moment versus curvature will be in error. In addition, fiber orientation and asymmetry occasionally may make selection of samples difficult. In general, the instrument is best suited to homogeneous samples which can be prepared in rectangular flat strips of uniform cross-section and width. The use of a proper tissue slicer, which can excise samples of 0.040–0.120 in. thickness and control this thickness within a narrow tolerance, is a prerequisite to any larger scale applications of the Bending Tester. The equation for the moment of inertia $I = \frac{1}{12} bT^3$ shows that the thickness T has a much more important effect than the width b. Using an accurately adjusted and preferably automatic device, a shorter preparation time, a better control of thickness, and a smaller scatter of experimental points can be expected.

6. Conclusions

Testing by bending can be employed as a method of measuring rheological properties of solid materials. The fundamental bending parameters which the MITEX MK II Bending Tester measures are: bending moment (lb in), curvature (in^{-1}), bending rigidity (lb in^2), modulus of elasticity (lb in^{-2}), curvature set (in^{-1}), and bending moment loss (lb in). These parameters are 'fundamental' because they describe

bending properties of all materials. This paper presented information on the feature of the new instrument and discussed a number of equations related to bending Values of the modulus of elasticity obtained for samples of celery, carrot, apple an potato were close to those reported in the literature using other methods. The effec of environmental conditions on the mechanical properties could be easily followe on the same strip of sample mounted on the instrument. Empirical transposition an extrapolation of the plots of the modulus of elasticity versus testing time, and math ematical functions derived therefrom provided information on the probable valu of the modulus of elasticity immediately upon cutting, and on the approximate ag of the particular sample. The relationship between the bending properties of th material and sensory descriptions of crispness and other textural characteristic related to turgor deserves a separate investigation.

Our experience indicates that only samples which are uniform and can be cut int rectangular flat strips of accurately controlled thickness and width are suitable fo testing by this method. If these conditions are satisfied, the instrument provides convenient and simple means for the measurement of rheological properties c materials of plant origin and possibly of other foods.

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